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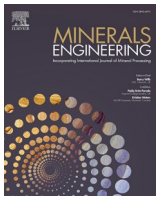

Material extraction potential of desalination brines: A technical and economic evaluation of brines as a possible new material source

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ABSTRACT

The environmental threat of discharging highly saline desalination brine into the sea and an expected growth in global demand for raw materials have increased interest in the idea of integrating desalination and material extraction. This paper examines the material extraction potential of desalination brines corresponding to the seawater desalination volume required to meet the projected global demand for freshwater. The results show that a growing use of seawater desalination techniques to solve the upcoming high water stress provides an increased material extraction potential by 2050, particularly for highly concentrated materials. For example, in the studied scenario, the extraction potential for magnesium and lithium in 2050 is approximately 2243 and 3.1 times the corresponding 2018 production, respectively. The analysis shows that the estimated lithium potential may be sufficient to ameliorate the expected shortage over this century, while the magnesium potential can significantly exceed the future demand. Several seawater materials with low concentrations do not have adequate 2050 extraction potential to be considered a viable resource even compared to present production. This study shows that the promising resource potential of desalination brines for elements such as lithium requires development of suitable extraction techniques that overcome the identified techno-economic challenges.

1. Introduction

The anthropogenic global warming is the broadly recognised threat, which may result in dramatic changes in the Earth's ecosystems and may even lead to civilisation collapse (Diamond, 2011; Masson-Delmotte et al., 2018; The EIU, 2019). To mitigate such impacts, it is necessary to achieve the Paris Agreement goals by cutting causal greenhouse gas emissions from fossil fuels to zero by 2050 and set forth on a path to net-negative emissions to compensate the environmental damage of climate change (IPCC, 2015; Rogelj et al., 2018; UNFCCC, 2016). Global defossilisation through transitioning to sustainable technologies and adopting renewable electricity generation forms (REN 21, 2020) will require according to different scenarios up to 11-fold capacity growth by 2050 for wind (EC, 2020; IEA, 2019; IRENA, 2019a; The EIU, 2019), increase from the current 627 GW (REN 21, 2020) to up to 70,000 GW for solar photovoltaics (PV) (Bogdanov et al., 2021; EC, 2020; Haegel et al., 2019; IRENA, 2019b), while global battery electric vehicles (BEV) sales are expected to reach a share of 70% of all vehicles or more (DNV GL, 2020; Greim et al., 2020; Khalili et al., 2019; RBC, 2018). A rapid demand growth for raw materials is the result of the expected growth in demand for such renewable energy (RE) capacity (EC, 2020; Jones et al., 2020; Junne et al., 2020; Sovacool et al., 2020). Some of the required materials are not only produced in small quantities at the present time but also have limited natural reserves, which may threaten the long-term sustainability of the energy transition (Ballinger et al., 2019; Junne et al., 2020; Watari et al., 2019). Elements that have the potential to be a bottleneck to the energy transition according to different studies include chromium, cobalt, copper, lithium, manganese, nickel, silver, tellurium, neodymium and dysprosium (Altermatt et al., 2018; Cristóbal et al., 2020; EC, 2016; Junne et al., 2020; Månberger and Stenqvist, 2018; Valero et al., 2018).

Another global challenge is deteriorating water security as a result of the population growth, industrial-scale agricultural production and climate change. RE-based seawater desalination technologies have been proposed as a possible approach to tackle this issue (Caldera and Breyer, 2020; Wada et al., 2014; WBG, 2019). Caldera and Breyer (2020) have shown that the ongoing significant reduction in the cost of RE technologies could strengthen the desalination sector by reducing the cost of energy required for continuous operations. As a result, seawater desalination would be able to meet water shortages in the decades to come in a cost-effective way.

The volumes of brine generated after the water desalination depend on an effectiveness of water recovery from feedwater and attaining an

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Nomenclature

BEV	battery-electric vehicle
ED	electrodialysis
HPIE	Highest Possible Irrigation Efficiency
IEP	Irrigation Efficiency Push
LCOE	levelised cost of electricity
LCOMat	levelised cost of material
PV	photovoltaics
RE	renewable energy
SWRO	seawater reverse osmosis
t	tonne (metric ton)
Mt	Megatonne
Li	Lithium
Mg	Magnesium

optimal plant operation to minimise its energy consumption (Jones et al., 2019). If a desalination plant has a recovery ratio of 50%, the brine discharge is a factor of two more concentrated with dissolved elements than the feedwater (Chelme-Ayala et al., 2013). The high salinity of such desalination brines, which is discharged back to the sea, has been causing environmental concern due to its potential impact on marine eco-systems (Gacia et al., 2007; Pistocchi et al., 2020). However, the projected high global desalination demand (Caldera and Breyer, 2020) may create new opportunities if the corresponding desalination brine discharge becomes a viable material source. Such possibility of extracting materials from desalination brines may address environmental concerns while also creating an added economic opportunity and helping to meet the growing demand of materials (EurecatNG, 2020). Sodium, potassium, magnesium and calcium are already commercially extracted from seawater (Bardi, 2010; Loganathan et al., 2017; Shahmansouri et al., 2015). However, to minimise the environmental impact of desalination brines, other elements should also be removed from the brine before its disposal into the environment. Consequently, options such as zero brine discharge are currently being proposed (Davis, 2006; Nayar et al., 2019).

As seawater contains volumes of materials that are many orders of magnitudes higher than those found on land (Loganathan et al., 2017), seawater should be considered as a potential source for meeting the material demand of future energy systems. The concentrations of some elements, which are dissolved in seawater, however, are very low, and their extraction thus requires further intensification processes. It is also claimed that the key factor limiting the growth of material extraction from seawater is the high energy intensity of such extraction processes and, therefore, the cost (Bardi, 2010). However, the possibility of achieving very low electricity cost levels due to the steady reduction in solar PV and battery costs (Vartiainen et al., 2020), increased demand for desalination to meet freshwater needs (Caldera and Breyer, 2020) and the corresponding growth in concentrated brine discharge may help to overcome these limitations. But such a potential benefit depends on the quantity of the extracted materials and its value in the future market.

As of now, no one has estimated the material quantity that desalination brines can contribute to meeting the future global material demand. This study analyses the overall material supply potential of the whole range of elements in desalination brine from desalination operations required to meet the global demand for desalinated water in 2050 and the technical challenges and opportunities related to material extraction. For an easier detailed examination, selecting some elements as a reference is the only convenient way. Thus, in this paper lithium (Li) is chosen as a representative for low concentration elements, while magnesium (Mg) stands for the highly concentrated elements.

2. Overview of material extraction from seawater and desalination brines

To get a clearer picture of the key issues of the present study, it is important to have a brief overview of the present activities regarding material extraction from seawater and the associated techniques as well as the challenges as outline in this section.

2.1. State of the art of materials extraction from desalination brines

Nayar et al. (2019) report a seawater desalination concept that can support the production of NaCl (99.8% purity) at a specific cost of 170 USD/t_{salt} alongside potable water at a cost of 3 USD/m^3 compared to the 2020 solar salt market price of 120 USD/t_{salt} (USGS, 2021). Another bench-scale study showed that using electrodialysis (ED) on a rejected stream of seawater reverse osmosis (SWRO) (Davis, 2006) enables the production of potable water and the extraction of NaCl, Br and Mg with an efficiency of 76%, 80%, 94% and 80%, respectively. Sano et al. (2018) reported that Mg of 99% purity can be extracted directly from seawater with up to 100% efficiency using ED and an ion exchange membrane technique at a theoretical extraction cost of 970 USD/t.

Ahmad et al. (2019) conclude that more than 78% of Mg in SWRO reject brines can be extracted economically from a large-scale desalination plant by chemical precipitation. The total cost of chemicals is reported to be 1300 USD/t_{Mg}. In turn, the magnesium market price has been within the range of 1825 USD/t_{Mg} to 2550 USD/t_{Mg} over the last 10 years (USGS, 2021). The process was stated to enable co-production of calcium, sulphur, boron, strontium and lithium with recovery efficiencies to be approximately 16%, 8%, 80%, 20% and 30%, respectively. However, higher recovery efficiencies are possible for single materials (no co-production) with other process parameters, and recovery rates can reach 90%, 82% and 67% for magnesium, boron and lithium, respectively.

SWRO technology accounts for the largest shares of desalination market today, and due to improving technical and economic characteristics, it is expected to be the dominant desalination technology in the coming years (GWI, 2022a, 2022b; Jones et al., 2019; WBG, 2019). Even though adding further processing loops like membrane distillation crystallisation can increase a water recovery to 88–100%, operational costs of such systems also increase (Quist-Jensen et al., 2016b).

2.2. Magnesium and lithium extraction from desalination brines

In this study, magnesium is taken as a representative for high concentration elements because not only it is one of the most abundant element in seawater, but it is also declared as a critical raw material (EC, 2017; USGS, 2018) due to the Chinese dominance on the global Mg production and its importance for the wind power industry (J. Kim et al., 2015), and the future automotive industry (Electric Vehicles Research, 2017; Takano, 2018). Similarly, lithium is used as a reference for materials found in seawater at low concentrations because it is also determined to be a critical material (EC, 2017; USGS, 2018) due to its importance for the growing battery application in power and transport sectors (Bogdanov et al., 2021; DB, 2016; Greim et al., 2020; Hache et al., 2019; Junne et al., 2020; USGS, 2021).

Generally, lithium extraction from salt lake brines is assumed to be economically and technically feasible when the Mg to Li ratio is less than 8:1 (Li et al., 2019; Zhao et al., 2013). The limitation occurs due to the similar chemistries of these two materials, which make a separate extraction of lithium more difficult. In addition to the low concentration of Li in seawater, the magnesium to lithium ratio of about 7000:1 in both seawater and desalination brines further complicates lithium extraction.

Fig. 1 presents a map of six possible Li extraction paths from SWRO brines.

Path 1 is a sketch of a purely theoretical technique of passive water removal through direct solar evaporation. The method requires low

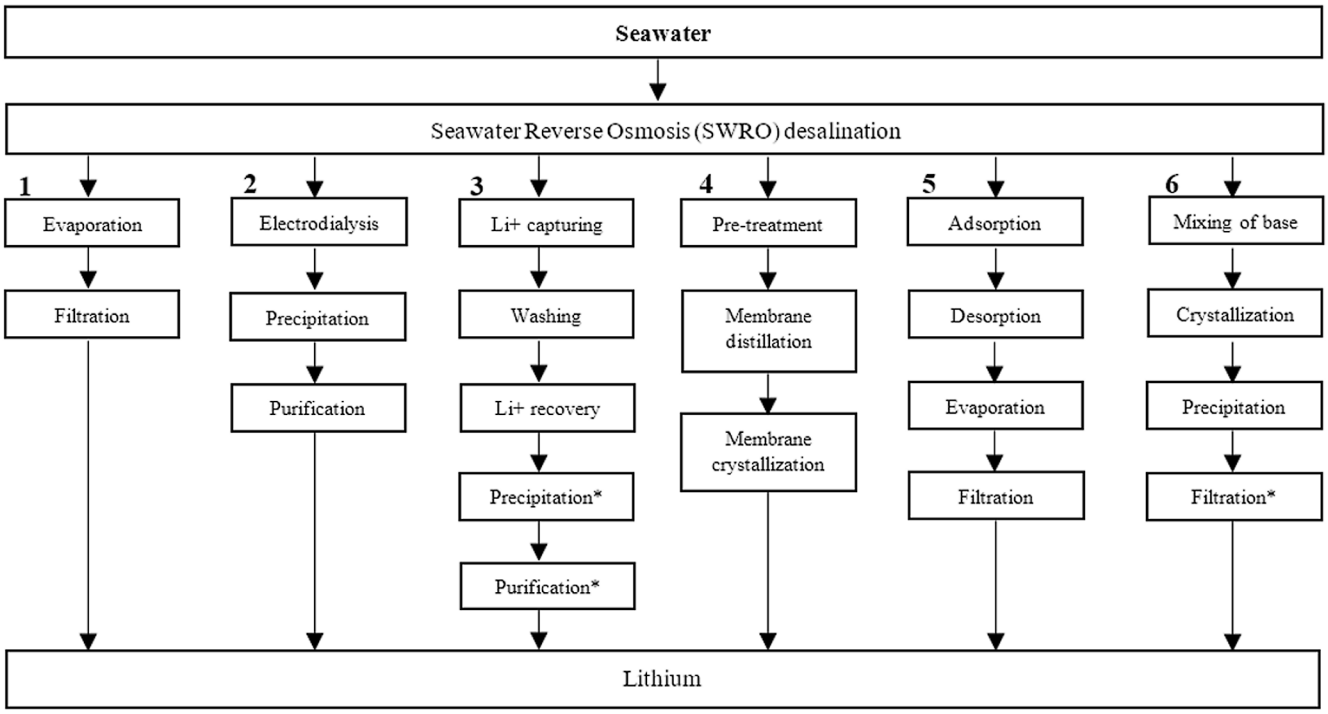

Fig. 1. A simplified map of possible Li production paths from desalination brines. (1) Theoretical; (2) Electrodialysis; (3) Electrochemical method; (4) Membrane technology; (5) Adsorption/desorption; (6) Chemical precipitation. * required processes that enable increased Li concentration and purity in solutions or powders. The processes can be flexibly adopted, combined and modified to attain better efficiencies.

investment and operational costs but unmanageable land size and long process time.

Path 2 is a process that combines electrodialysis using a lithium ionic superconductor, precipitation using a Na_2CO_3 and HCl recovery solution, and purification with water for extracting Li_2CO_3 from the solution (Hoshino, 2015). The method showed a scalable possibility to extract lithium in an energy efficient way, however, additional research is required to adopt it from seawater to desalination brine.

Path 4 is a membrane technology for Li extraction from a single salt LiCl solution using pre-treatment for $CaCO_3$ and $CaSO_4$ removal, vacuum membrane distillation for up to 80% water recovery, and membrane crystallisation for LiCl recovery (Quist-Jensen et al., 2016a). The method resulted in a modelled cost of 2180 USD/t_{Li}, showed good competitiveness compared to traditional Li extraction from salt lake brines (2000–3000 USD/t_{Li}). However, the study presented only a lab-scale setup and further research is required to demonstrate Li extraction from mixed salt solutions to show how the concept can be applied to desalination brines.

Path 5 is an adsorption/desorption process using a MnO_2-based adsorbent and HCl resin desorption, vacuum evaporation and filtration adsorption (Loganathan et al., 2017). Generally, such a method is a combination of cheap and well-known adsorption and desorption processes that are used for water purification. It potentially allows to concentrate seawater elements of low concentration. However, besides that the method is only presented in laboratory scale studies and is needed to be adapted to desalination brines, the competition of high-concentrated elements in water solutions cause additional difficulties.

Known paths that have reported Li production from desalination brines are path 3 and path 6. The other paths are theoretical options based on literature sources of future desalination schemes as well as Li extraction from seawater and geothermal brines (Hoshino, 2015; Loganathan et al., 2017; Quist-Jensen et al., 2016a), which can have a higher concentration of Li. Economical Li extraction from desalination brine is challenging because of the 8,000 times lower Li concentration (Munk et al., 2016) compared to the concentration in salt lakes.

Path 6 describes precipitation using a mix of a base with NaOH, crystallisation in an oven, room temperature precipitation, filtration with a Büchner funnel process under vacuum, and additional filtration for Li_2CO_3 separation (Ahmad et al., 2019). Li extraction based on this approach may hold out some promise because the costs will be shared by the extraction of other elements, such as Mg, if further optimisation of Li extraction is achieved. However, from the perspective of extraction of materials found at low concentration, it should be noted that due to the presence of multiple materials and their complex interactions, some processes may be more effective for extraction of one element than others, leading to a variety of possible optimal paths.

Path 3 is an electrochemical method that integrates selective electrodes, precipitation and purification to promote Li concentration (Joo et al., 2020; Kim et al., 2019). Such a novel concept of Li recovery directly from desalination brines using an electrochemical system has been demonstrated by Kim et al. (2019). The extraction utilises λ-MnO_2/Ag electrodes in a two-cycle process. The chemical reaction of the process is:

$$xLi^{+} + xe^{-} + 2\lambda - MnO_2 \rightarrow Li_xMn_2O_4 \quad (1)$$

$$Ag + xCl^{-} \rightarrow AgCl_x + xe^{-} \quad (2)$$

The process can be repeated multiple times using even more concentrated solutions of previous cycles to reach a highly concentrated Li solution. Li purity, extracted from 0.43 mg/L (2.5 times that of seawater) of Li concentrated feedwater, is 56% and 99% after completion of the 1st and 2nd cycle, respectively. In turn, one cycle takes 17.4 h and 21 min for the capture and release of Li, respectively. The energy consumption of the system is 3.07 kWh/kg_{Li} (Joo et al., 2020; Kim et al., 2019), which represents less than 5% of the lithium value. The practical capacity of $\lambda - MnO_2$ electrodes is 7.34 $mg_{Li}/g_{\lambda\text{-}MnO2}$ and the capacity of the silver electrode is estimated to be 115 $mg_{Cl}/g_{electrode}$.

While the low energy demand appears promising, the driving cost of the production will depend on the cost of the electrodes. Cost-effective manganese oxides, required for the $\lambda - MnO_2$ electrode, are available,

leaving the challenges being the cost of silver, the silver electrode efficiency and lifetime. Kim et al. (2019) and Joo et al. (2020) claim that a system with these electrodes is completely regenerable and can be used continuously. However, Srimuk et al. (2019) report that the Ag/AgCl electrode can lose up to 35–40% of its capacity after the 15th cycle, but the capacity stabilises after the loss and remains unchanged thereafter. Available research on Li extraction from desalination brines with an λ-MnO_2/Ag system does not provide clear information about system reusability (Zhao et al., 2019). Battistel et al. (2020), however, suggest accounting for electrode costs as operational expenditures assuming a lifetime of 30 cycles.

Considering the mentioned extraction techniques, which are available nowadays, and reported material production, path 3 was chosen as the best option for the further analysis of possible Li extraction potential from desalination brines, while path 6 was chosen as a technique to extract Mg.

3. Methods and data

Due to its multidisciplinary nature, this study requires combining various theories and data collected from different sources. This section briefly describes the sources of the used data and the methods implemented.

3.1. Global desalination demand scenario

In the study by Caldera and Breyer (2020), the global desalination demand by 2050 is estimated to be in the range of (1700–4400)·10^6 m^3/day, compared to the 40·10^6 m^3/day installed capacity in 2015. Such a demand is calculated for three scenarios using a modified LUT Energy System Transition Model (Bogdanov et al., 2019; Caldera and Breyer, 2020) at 5-year intervals from 2015 to 2050 based on assumed irrigation improvement options for the business as usual (Base) scenario, an irrigation efficiency push (IEP), and the highest possible irrigation efficiency (HPIE) (Supplementary Figure S1). The study structured the world into 145 regions and it thus provides desalinated water demand at this spatial resolution.

The IEP desalinated water demand scenario was taken as the key input for the current research in order to analyse the middle path approach. Even though the HPIE scenario shows lower demand in 2050, it is the most ambitious and optimistic scenario of the three scenarios. The Base scenario forecasts severe water stress compounded by poor water utilisation efficiency, which may be too pessimistic.

3.2. Global water salinity and concentration of elements in seawater

Seawater contains various dissolved minerals which determine its salinity. Average global seawater salinity is usually about 3.5%, or 35 g/kg, but it differs between locations depending on local human activities and factors such as freshwater evaporation from seawater due to high temperatures and freshwater addition from rivers or melting ice. The data on global seawater salinity used in this work was derived from the National Oceanic and Atmospheric Administration Database (NOAA, 2020) as a statistical mean of averaged decades of surface water salinity on a 1° × 1° grid (Supplementary Figure S2). Based on the dataset, the seawater salinity was determined for each of the 145 regions as the average of the region's coastline surface seawater salinity. While seawater salinity differs between locations, the element composition of seawater, in turn, is stable and the proportions of dissolved elements are constant regardless of the total seawater salinity. The defined seawater salinity was then correlated with proportions of elements in the seawater to find the material concentrations for each of the 145 regions.

The proportion of elements estimated at 35,000 ppm was reported by Turekian (1968) and reproduced in SeaAgri (2015). A full list of seawater elements and their concentrations are provided in the Supplementary Material (Table S1). The table shows that seawater concentration of elements ranges from higher than approximately 19,400 parts per million (ppm) for chlorine, to approximately 1.3·10^{-5} ppm and less for rare earth elements, such as yttrium. The Li content in feedwater of 35,000 ppm is 0.17 ppm, whilst the concentration of Mg is 1290 ppm. The major extraction challenge of Li compared to Mg is attributed to the large concentration difference between these elements.

3.3. Global and region level material potential in desalination brines

The volumes of brine utilised in all the 145 regions are based on the data of demand for desalination. For land-locked regions with water stress and no access to the coast, brine discharge corresponding to their desalinated water needs were calculated by interlinking to desalination plants operating in the closest regions with open water coastline access (Supplementary Table S2).

Brine volumes are calculated using Equation (3):

$$Q_b = \frac{Q_d}{RR} \cdot (1 - RR) \tag{3}$$

where Q_b is the volume of produced brines in m^3/day, Q_d is desalinated water production (plant capacity) in m^3/day, and RR is the recovery ratio of the desalination plant (efficiency of desalination).

The recovery rate is set to 50%, which corresponds to the optimal recovery rate of a SWRO desalination plant (Childres, 2017).

The brine salinity is calculated using Equation (4):

$$S_b = \frac{S_f}{1 - RR} \tag{4}$$

where S_b is the salinity of the produced brines in kg/m^3 and S_f is the feedwater salinity in kg/m^3.

The material potentials of desalination brines are calculated based on the brine volumes and their salinity at region and global levels for the Base, IEP and HPIE scenarios from 2015 to 2050. The annual values of material potential are also calculated for a reference plant with a capacity of 10^6 m^3/day in order to elaborate the challenges and techno-economic improvements needed. An economically optimal extraction efficiency was set as 80% regardless of the material type because the only known study providing an estimate of materials recovery efficiencies reported a Li extraction rate from desalination brines of up to 67% and 78% for magnesium (Ahmad et al., 2019).

In addition to studying the material potential, it is instructive to investigate the extent to which these materials could contribute to easing material resource limitations, for which Li is a good example. Thus, three of the eight scenarios for Li demand projection from the present to the year 2100 from Greim et al. (2020) were selected for analysis of the contribution of these desalination brine resources to amelioration of pressure on Li supply shortage to the end of this century. The selected scenarios correspond to the highest, median and lowest identified fresh Li demand by 2050. Li demand corresponding to the eight scenarios is presented in the Supplementary Material (Figure S3). The names of the three selected scenarios are BPS 3bn, BPS 3bn LDV LR, and BPS 3bn LDV V2G, as defined by Greim et al. (2020), indicating a best policy scenario (BPS) leading to 3 billion light-duty vehicles (LDV) with scenario variations for low recycling (LR) and vehicle-to-grid (V2G) impact.

3.4. Estimating techno-economic performance of Li extraction from desalination brines

The economic feasibility of Li extraction from the case plant's desalination brine discharge was estimated using the electrochemical method with the λ-MnO_2/Ag electrode system (path 3). Such a method is the only one available, in frames of which a selective Li production from desalination brines was reported at a proven efficiency, yield, and energy requirement on a laboratory scale level. The economic efficiency of the method can be calculated by applying a simple systematic

calculation based on the present market value of silver for the electrode and produced lithium.

According to Faraday's laws of electrolysis (Hibbert, 1993) and the principles of stoichiometry, the theoretical capacities of electrodes can be estimated using the Faraday constant, molar masses of the electrodes, and the theoretical specific capacities of Li^+ and Cl^-. Alternatively, the theoretical capacity can be adopted to the present case using the molar masses of the electrodes and the molar masses of the Li and Cl to be recovered using Equations (5) and (6):

$$Q_{th_{\lambda-MnO_2}} = \frac{\frac{F \bullet n_{CC_{Li^+}}}{M_{LiMn_2O_4}}}{Sc_{Li}} = \frac{M_{Li}}{M_{LiMn_2O_4}} \tag{5}$$

$$Q_{th_{Ag}} = \frac{\frac{F \bullet n_{CC_{Cl^-}}}{M_{AgCl}}}{Sc_{Cl}} = \frac{M_{Cl}}{M_{AgCl}} \tag{6}$$

where Q_{th} is the theoretical capacity of the electrodes, F is the Faraday constant of 26.801 A·h/mol, n_{CC} is the number of the charge carrier, M is the molar mass in g/mol, and Sc is the theoretical specific capacity in A·h/g.

While the amount of Li to be recovered from the brine is determined by the brine flow, the amount of Cl taken up by the Ag/Cl electrode (m_{Cl}) can be estimated as follows:

$$m_{Cl} = n_{Cl} \bullet M_{Cl} = \frac{m_{Li}}{M_{Li}} \bullet M_{Cl} \tag{7}$$

where m is the mass in g and n is the amount in mol.

Molar masses of Li, Cl, $LiMn_2O_4$, and AgCl are 6.94, 35.5, 180.94, and 143.4 g/mol, respectively.

In 2019, silver cost approximately 521 USD/kg as compared to 13 USD/kg for Li (USGS, 2021). In the last 10 years, the lithium market price has fluctuated between 5.18 and 17 USD/kg (USGS, 2021). Nevertheless, the price is expected to stabilise at a level of 10 USD/kg due to the market supply and demand equilibrium and production growth (Sterba et al., 2019). The applied concept of levelised cost of material (LCOMat) given in Equation (8):

$$LCOMat_{Li} = \frac{capex_{process} \cdot crf_{process} + opex_{fixed} + opex_{lostelectrode}}{TLi} + opex_{varprocess} \cdot SEC \tag{8}$$

where $capex_{process}$ is the capital expenditures of the electrochemical process in USD, $crf_{process}$ is the annuity factor for the electrochemical process, TLi is the total Li produced in a year in t, $opex_{fixed}$ is the fixed annual operational expenditures of the electrochemical process in USD, $opex_{lostelectrode}$ is the fixed annual expenditures of the lost electrode value in USD, $opex_{var\ process}$ is the variable opex of the electrochemical process and is equal to the levelised cost of electricity (LCOE) of the process in USD/kWh, and SEC is the specific energy consumption in kWh/kg_{Li}.

Due to the lack of information regarding the capital and variable expenditures of the specified extraction plant, a proxy process is applied as an estimate using the related expenditure of an industry-scale electrolyser plant (Fasihi et al., 2021). Accordingly, the capital expenditures of the process are derived from the annual electricity demand for Li extraction and capital expenditures of the electrolyser process assuming a 90% plant utilisation rate using the following equation:

$$\mathbf{capex}_{process} = \frac{TLi \cdot SEC}{FLH} \cdot capex_{\mathbf{electrolyser}} \tag{9}$$

where $TLi \cdot SEC$ is the annual electricity demand of the process in kWh/year, FLH is the full load hours of the process in a year, and $capex_{electrolyser}$ is the capital expenditures of the electrolyser process in USD/kW.

The annuity factor of the electrochemical process is quantified using Equation (10).

$$crf_{plant} = \frac{WACC \cdot (1 + WACC)^N}{(1 + WACC)^N - 1} \tag{10}$$

where $WACC$ is the weighted average cost of capital in percent, and N is the lifetime of the electrolysis plant in years.

Following Fasihi et al. (2021), WACC is set to 7%, capex is 204 €/kW for the year 2050, and $opex_{fix}$ is 3.5% of capex. The lifetime of the electrochemical process setup is assumed to be 20 years. LCOE of 50 €/MWh is taken from the research by Caldera and Breyer (2020), applying a long-term average exchange rate of 1.1 USD/€.

In estimation of the operational costs related to the Ag electrode, silver recovery through recycling at the end of the electrode life was assumed. At present some industries offer 85% of the price of silver for silver scrap with purity higher than 92.5% (RioGrande, 2020). In the case of an Ag electrode with lower purity, the scrap value is lower due to the need for more processing. However, for this study the cost calculation is done for the parameter range of 85% to 99% assuming possible process improvements and the potential benefit that comes with industrial scaling. The consideration of recycling allows recovery of a substantial share of the initial cost of the silver or repeated use of a few batches of electrodes by covering the cost of recycling silver. Note that in such scenarios the cost of electrode manufacturing is assumed to be negligible. To estimate the overall potential silver requirement per year, a simplifying assumption was adopted that uses two sets of electrodes in a continuously rotating manner with 50% in use for Li extraction while the remaining electrodes are in the recycling process. It should be noted that the mass of each electrode set should have a capacity that is sufficient for the whole Li mass uptake from the solution. Taking into account possible Li market price variations in a range of 20–30%, the economic evaluation is performed as a matrix of LCOMat based on variations of two parameters, namely the electrode scrap value at the end of the electrode lifetime and possible improvements of electrode life from 30 to 300 cycles.

4. Results

This section presents the findings of the analysis that was performed to understand global material potential of desalination brines.

4.1. Global material potential of desalination brines

The 2050 global material extraction potential of the 15 most concentrated elements in seawater is presented in Table 1 and material potential of the whole range of seawater elements is given in the Supplementary Material (Table S1). The data shows that while the extraction potential of high-concentrated elements from desalination brines is very large, it may not be suitable as a source for low-concentrated elements without processes that allow co-production of such elements or sub-processes that may enhance the economic and technical viability of extraction.

4.2. Regional material potential of desalination brines

The brine volumes on a regional level for the IEP scenario in 2050 are presented in Fig. 2. The largest amounts of brine are found at the coasts of Pakistan, China, the United States, Iran, India, Ukraine and Moldova, Saudi Arabia, and Russia.

The 2050 theoretical potential of Li and Mg in desalination brines for the IEP scenario, distributed over the 145 regions of the LUT model, is shown in Fig. 3. Compared to the 95 kt Li production in 2018, the 2050 potential of Li in brines for the IEP scenario at an 80% material extraction efficiency is approximately 3.1 times higher at about 294 kt/y.

The top 15 countries with the highest share of the global lithium extraction potential from desalination brines are presented in Fig. 4.

Table 1
The 2050 material extraction potential of the 15 most concentrated elements in seawater for the business as usual (Base), an irrigation efficiency push (IEP), and the highest possible irrigation efficiency (HPIE) scenarios.

№	Material	Formula	Concentration in seawater [ppm]	Material potential [Mt/y]						2018 production [Mt]	2050 potential of the IEP scenario at 80% efficiency [% 2018 production]
				Base		IEP		HPIE			
				100%	80%	100%	80%	100%	80%		
1	Chlorine	Cl	19,400	61,381	49,104	41,996	33,597	22,706	18,165	286	18,287%
2	Sodium	Na	10,800	34,171	27,337	23,379	18,703	12,640	10,112		
3	Magnesium	Mg	1290	4081	3265	2793	2234	1510	1208	1	224,300%
4	Sulphur	S	904	2860	2288	1957	1566	1058	846	79	1972%
5	Calcium	Ca	411	1300	1040	890	712	481	385	568	125%
6	Potassium	K	392	1240	992	849	679	459	367	36	1889%
7	Bromine	Br	67.3	213	170	146	117	79	63	0,36	32,196%
8	Carbon	C	28	89	71	61	48	33	26	no data	no data
9	Nitrogen ion	N	15.5	49	39	34	27	18	15	144	19%
10	Strontium	Sr	8.1	26	21	18	14	9	8	0,22	6376%
11	Boron	B	4.45	14	11	10	8	5	4	3,85	200%
12	Silicon	Si	2.9	9	7	6	5	3	3	7,40	68%
13	Lithium	Li	0.17	0.54	0.43	0.37	0.29	0.20	0.16	0,10	310%
14	Rubidium	Rb	0.12	0.38	0.30	0.26	0.21	0.14	0.11	no data	no data
15	Phosphorus	P	0.09	0.28	0.22	0.19	0.15	0.10	0.08	21	0.72%

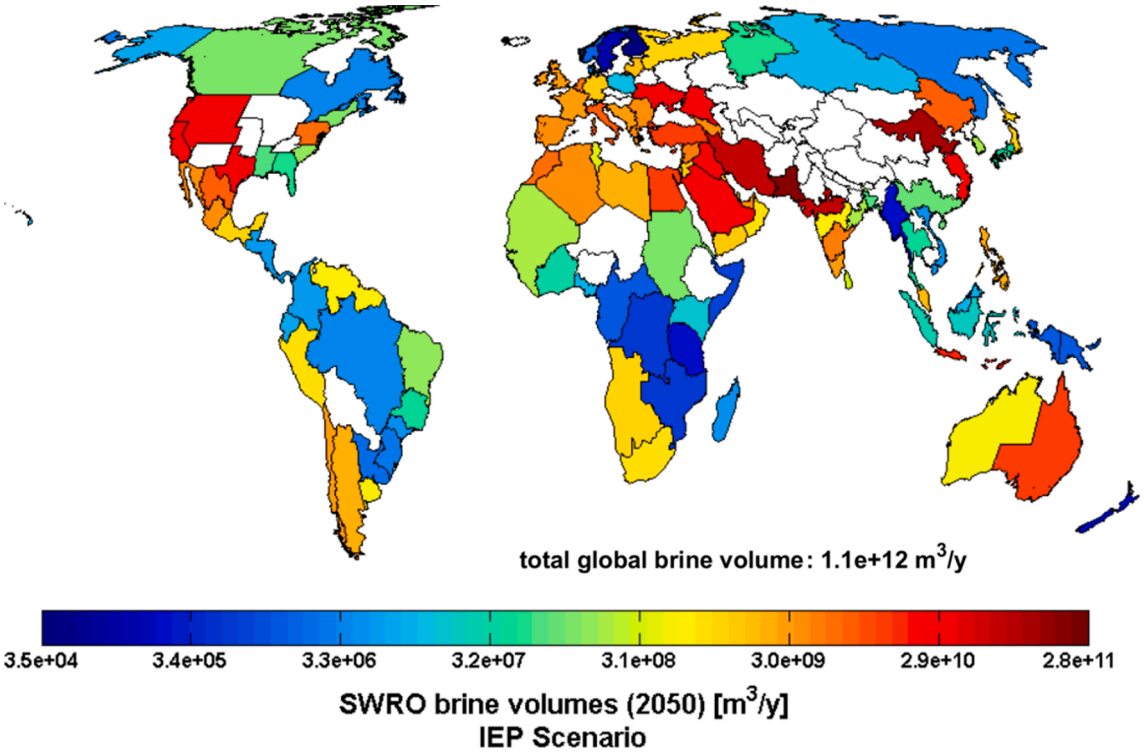

Fig. 2. Global seawater reverse osmosis (SWRO) brine production for the irrigation efficiency push (IEP) scenario in 2050.

Pakistan leads with the highest share of approximately 27% of the annual lithium extraction potential by 2050, with China, the United States and Iran following with shares of approximately 15%, 11% and 10%, respectively.

By comparison, the first and 10th country, namely Pakistan and Indonesia, could extract about 79.6 and 5.2 kt lithium per year, which is 84% and 5% of the global Li production as of 2018, respectively. These numbers show that if such an extraction potential could be achieved economically, present water stress could be converted into an opportunity.

The Mg content of SWRO desalination brines for the IEP scenario in 2050 with 80% potential material recovery is 2230 Mt, which is 2240 times larger than the 0.9 Mt produced globally in 2018 (USGS, 2021). The most resource rich countries for Mg are the same as the top countries in terms of the Li potential in desalination brines, as summarised in Fig. 4. The theoretical amounts of the Mg potential in desalination brines of all the top 15 countries in 2050 is by magnitudes higher than the global magnesium production in 2018.

The 2050 potential extraction of both Li and Mg from brines is higher than the present production. The trend of the production increase from the current time to 2050 can be inferred from the corresponding global trends depicted for Li and Mg in Fig. 5 and Fig. 6, respectively. Table 1 also shows that not all materials can achieve a 2050 potential higher than the corresponding 2018 production. As can be seen from the value of 2050 material potential as a percentage of 2018 production, most of the top 15 highly concentrated materials show a huge increase.

Table 2 presents a list of the top 15 elements based on relative value compared to the respective 2018 production. Materials outside this list

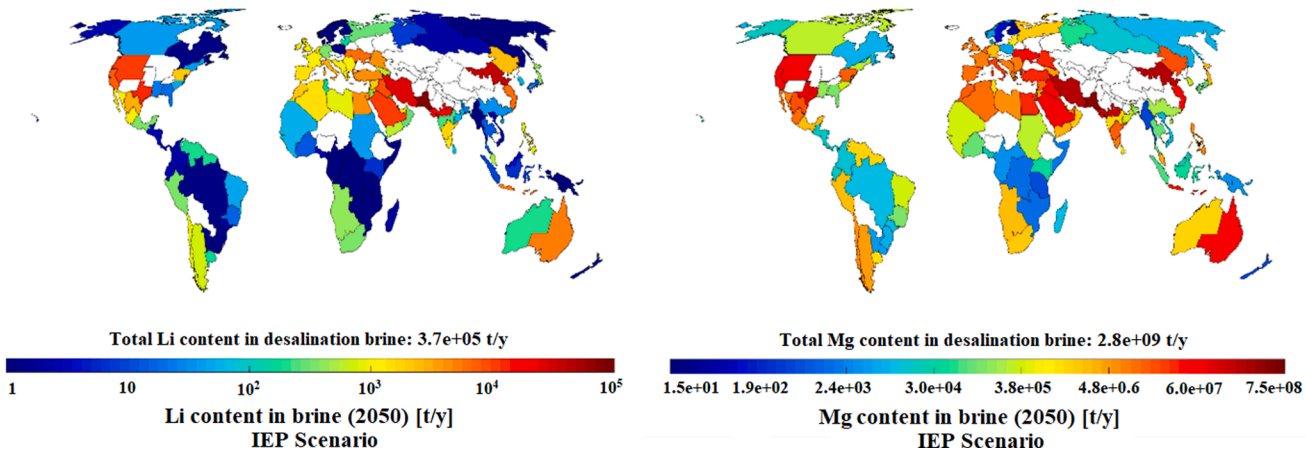

Fig. 3. Global Li (left) and Mg (right) content in desalination brines for the irrigation efficiency push (IEP) scenario in 2050.

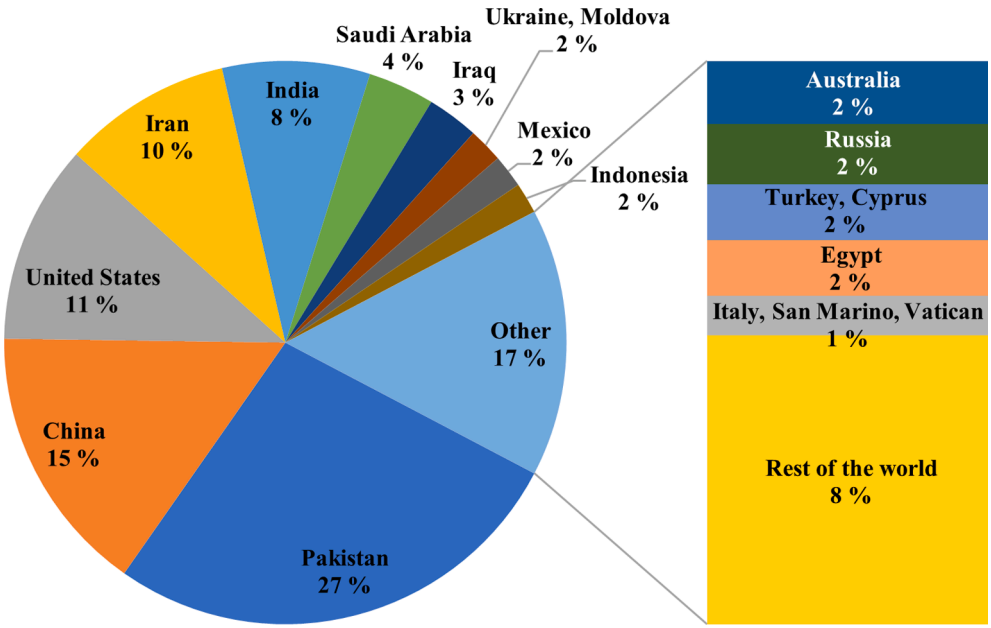

Fig. 4. Top 15 countries with the highest share of the global lithium extraction potential from desalination brines.

cannot be regarded as a resource because they do not amount to 30% of the present production.

The substantial increase in Mg seawater potential shows that the extraction can be higher than the demand. Li has not yet achieved any economic production from seawater or desalination brine, although a significant rise in demand is expected (Greim et al., 2020) (see Supplementary Material Figure S3). The future contribution of Li from desalination brine to the global supply potential will be limited compared to the magnitude of projected Li demand. The desalination brine-based Li extraction potential in 2050 as a share of the fresh Li demand is presented in Fig. 7 for the three selected scenarios, namely BPS 3bn, BPS 3bn LDV LR, and BPS 3bn LDV V2G. The share of the desalination brine-based Li potential from the present to 2050 for the three fresh Li demand scenarios is also shown in the Supplementary Material (Figure S4 to S6). The share grows as desalination volumes increase and reaches a Li supply potential of 27% by 2050 for the combination of the IEP scenario and the base case fresh Li demand projection (BPS 3bn), and up to 33% for demand scenario variations with reduced Li demand. Fig. 7 shows that the share changes with the magnitude of the Li demand. If the post-2050 desalination demand is assumed to remain approximately at the 2050 level, one can expect the same continued amount of Li production from desalination brines for the remaining half of this century. On the other hand, Supplementary Figure S3 shows that fresh Li demand will decrease significantly during the same period except for a scenario variation which assumes low input from recycling. Consequently, the share of Li from desalination brine increases steadily in the second half of the 21st century. Thus, depending on several other factors, Li extraction from desalination brine may bring another opportunity that may partly ameliorate the potential pressure of Li demand through this century, which may be of considerable importance to de-bottleneck the overall tight Li supply.

4.3. *Techno-economics of Li extraction from desalination brines*

Table 3 presents daily Li and Mg extraction potentials for the specified desalination plant and summarises the relation between extraction potential and sea salinity. The table shows that the less saline regions may need to invest more to close the material supply–demand gap of the future.

The electrodes capacity requirement for the electrochemical method of Li extraction and associated to it cost are calculated using Equations (5) and (6), leading to the theoretical electrode capacities:

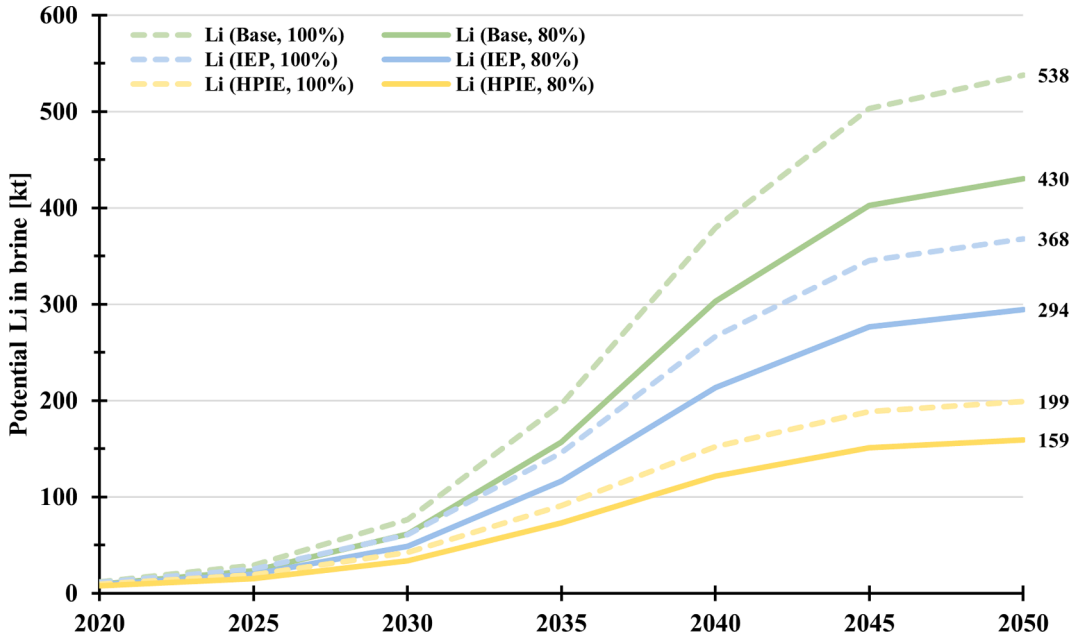

Fig. 5. Trend of global lithium production potential from brines of the business as usual (Base), an irrigation efficiency push (IEP), and the highest possible irrigation efficiency (HPIE) scenarios at material recovery efficiency of 80% and 100%.

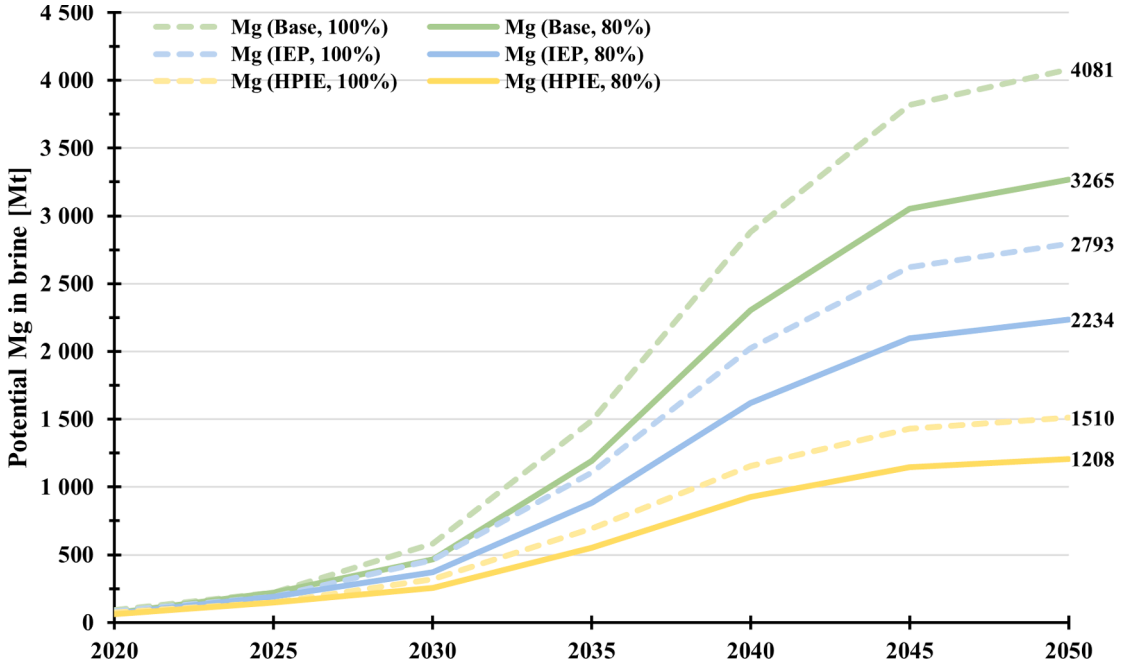

Fig. 6. Trend of global magnesium production potential from brines of the business as usual (Base), an irrigation efficiency push (IEP), and the highest possible irrigation efficiency (HPIE) scenarios at material recovery efficiency of 80% and 100%.

$$Q_{th_{\lambda-MnO_2}} = \frac{6.94g/mol}{180.94g/mol} = 38.3mg_{Li}/g_{\lambda-MnO_2}$$

$$Q_{th_{Ag}} = \frac{35.5g/mol}{143.4g/mol} = 248mg_{Cl}/g_{AgCl}$$

Thus, the practical capacity of a $\lambda - MnO_2$ electrode is 20% of its theoretical capacity. Similarly, the practical capacity of silver electrodes is about 50% of the theoretical maximum. Based on Equation (7) and a Li content in brines of 272 kg/day, the daily mass of Cl for uptake by Ag/Cl electrodes is:

$$m_{Cl} = \frac{272kg}{6.94kg/kmol} \bullet \frac{35.5kg}{kmol} = 1391kg$$

The estimated total recovery rate of Li becomes 10.1 $mg_{Li}/g_{\lambda\text{-}MnO2}$/day based on a 17.4-hour electrochemical cycle (Kim et al., 2019). With the same cycle time, a recovery rate of the *Ag* electrode is then 159 $mg_{Cl}/g_{Ag\text{-}electrode}$/day. The theoretical demands for $\lambda - MnO_2$ and *Ag* electrodes to extract all Li from the case desalination plant output is:

$$m_{\lambda-MnO_2} = \frac{272kg_{Li} \cdot 10^{6\frac{mg}{kg}}}{day} \cdot \frac{g_{\lambda-MnO_2} \cdot day}{10.1mg_{Li}} = 27t_{\lambda-MnO_2}$$

Table 2
2050 material potential of the top 15 elements based on their relative volume compared to the respective 2018 production.

№	Material	Formula	Concentration in seawater [ppm]	2050 potential of the irrigation efficiency push (IEP) scenario at 80% efficiency [% 2018 production]	2018 production [kt]
1	Magnesium	Mg	1290	224,300	996
2	Bromine	Br	67.3	32,196	362
3	Sodium Chloride	NaCl	30,200	18,287	286,000
4	Strontium	Sr	8.1	6376	220
5	Sulphur	S	904	1972	79,400
6	Potassium	K	392	1889	43,300
7	Iodine	I	0.064	402	27.6
8	Lithium	Li	0.17	310	95
9	Boron	B	4.45	200	3849
10	Calcium	Ca	411	125	568,000
11	Scandium	Sc	0.000004	85	0.0082
12	Germanium	Ge	0.00006	80	0.13
13	Silicon	Si	2.9	68	7400
14	Selenium	Se	0.0009	56	2.81
15	Rhenium	Re	0.0000084	30	0.049

$$m_{Ag} = \frac{1391 kg_{Cl} \cdot 10^{6\frac{mg}{kg}}}{day} \cdot \frac{g_{Ag} \cdot day}{159 mg_{Cl}} = 9 t_{Ag}$$

It suffices to answer that extracting the 272 kg_{Li}/day results in 99.3 t_{Li}/year. Assuming continuous use of the silver electrode, its required value is doubled due to the suggested operating process of the electrode recycling. However, the lost electrode value only comes from the recycling process. The electricity required to extract 272 kg_{Li}/day is 1044 kWh/day or 381 MWh/year. The energy intensity of the process equals to 3.81 MWh_{el}/t_{Li}. This estimate presents the electricity needed for a specific lab-scale process. The electricity demand for an industry-scale plant may require further automation of the extraction process, while process improvements may lead to lower energy demand, so that this estimation should be considered a first indicator and a lower energy intensity for extraction of Li could be achieved. The development of economically feasible extraction techniques for materials with low concentration in seawater depends on devising effective extraction paths.

The economic evaluation results of the Li extraction from desalination brines using the electrochemical process in the reference plant quantified in Equations 8–10 and using LCOMat are presented in Table 4.

Li extraction from desalination brines using the electrochemical process is not economically feasible with current available techniques. However, technical improvements may significantly reduce the cost of the extraction. Although the current technology does not allow economical mining of Li, a lifetime increase from 30 to 100 cycles combined with a scrap value improvement may push the production costs within the range of Li market price variation. A further electrode lifetime improvement to 300 cycles increases the chance of entering this range at current values for Ag scrap. The same applies to increasing the scrap value to 99% but this would lead to a narrow margin of negligible price for the recycling process (as recycling loss may likely be in excess of 1%), which may be too optimistic. Note that this calculation is based on an assumed 100% efficiency of recycling. If this efficiency is not achieved, even a projected promise of technical improvements may make the use of silver electrodes unviable.

Table 3
Daily Li and Mg extraction potential for a 1 million m^3 per day desalination plant at various sea salinity levels.

Seawater salinity [ppm]	Li potential [kg/day]		Mg potential [t/day]	
	100%	80%	100%	80%
35,000	340	272	2580	2064
40,000	389	311	2949	2359
18,000	175	140	1326	1061
6,000	58	47	442	354

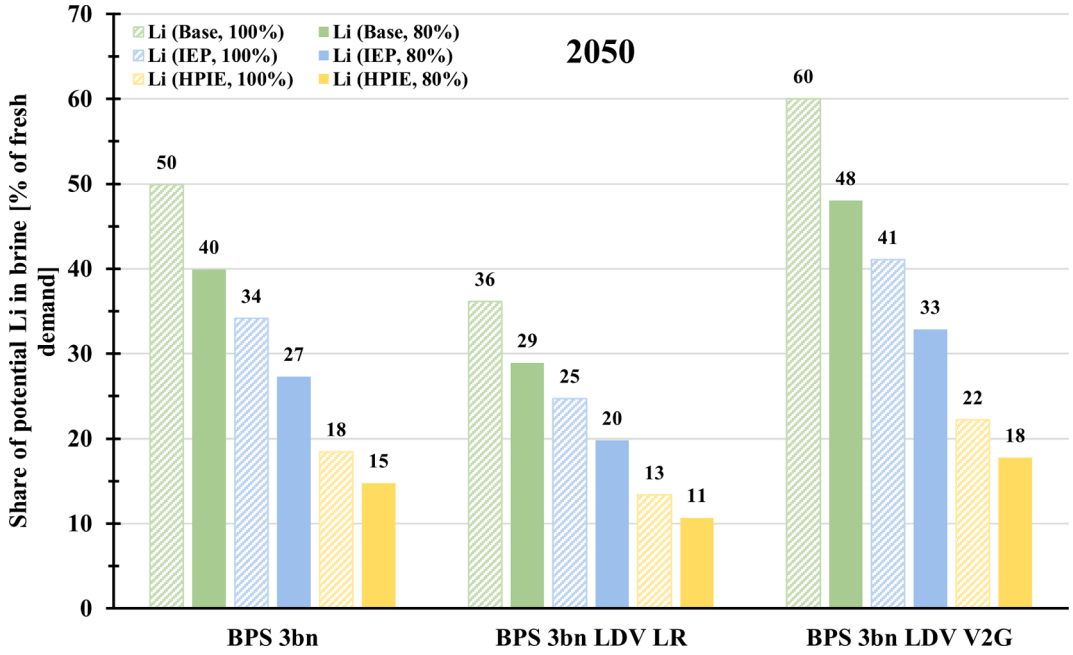

Fig. 7. Desalination brine-based Li supply potential in 2050 for the business as usual (Base), an irrigation efficiency push (IEP), and the highest possible irrigation efficiency (HPIE) scenarios as a share of fresh Li demand scenarios BPS 3bn, BPS 3bn LDV LR, and BPS 3bn LDV V2G (indicating a best policy scenario (BPS) leading to 3 billion light-duty vehicles (LDV) with scenario variations for low recycling (LR) and vehicle-to-grid (V2G) impact).

Table 4
Levelised cost of material (LCOMat) matrix of Li extraction from desalination brines based on the two key parameters of electrode cycles and Ag scrap value. The colour code indicates the relative economic attractiveness with a traffic light rating system.

LCOMat [USD/kg]				
		Electrode lifetime [cycles]		
		30	100	300
Fractional scrap value [%]	85	116	35	12
	90	78	23	7.9
	95	39	12	4.1
	99	7.9	2.5	1.0

The assumed hypothetical operational scenario leads to a global Ag demand of up to 51 kt in total for extraction of the entire Li potential in desalination brines for the projected desalination demand in the year 2050. The total Ag demand for the maximum projected Li production in 2050 exceeds the global Ag production of 2018 by a factor of 1.9. However, the continuous accumulation of recycled Ag stock could be used to augment the demand that is growing over a period of 15 years at an average annual production share of about 13%.

The theoretical amount of Mg in the desalination brines of the specified plant is 753 kt/year. Applying Mg extraction techniques corresponding to path 6 of Fig. 1, which is possible for reported 78 % Mg extraction, leads to 587 kt of Mg to be precipitated annually. The Mg potential per plant is about 7600 times higher than the corresponding Li potential, which from the business perspective does not allow stable co-production of Li and Mg.

5. Discussion

Increasing the concentration of materials in seawater through desalination can facilitate the material extraction process. With the expected increase in seawater desalination to meet freshwater demand (Caldera and Breyer, 2020), material co-production can increase the availability of materials found in seawater at high concentrations. Regardless of any economic value that may be created from selling the materials, material extraction from brine provides benefits from a wider perspective. Processing of brines for materials extraction would make it possible for all regions around the world to have access to almost evenly distributed material reserves locally. This, in turn, can ease regions' dependencies on material imports, especially for critical materials. However, due to the low concentration in seawater of many materials, extraction paths must be further improved to achieve economic viability.

As desalination increases, the availability of materials from highly concentrated salt brines could increase significantly depending on demand. If the technical challenges of extraction of materials at low concentrations are solved, water stress may become an opportunity for some locations. Regions that have high desalination water demand will also have large amounts of desalination brines and, hence, the availability of large amounts of dissolved materials in brines. Consequently, such water-stressed regions may become new locations for material mining. Based on the estimated material potential of future desalination brine, a large amount of materials will be available for extraction to meet both material demand for other economic activities and to avoid the release of concentrated brine into the environment (Pistocchi et al., 2020).

Closer study of Mg and Li shows that a large quantity of the two elements relative to the respective current production will be available by 2050. The Mg extraction potential, as an example of elements with high concentration, can be significantly greater than future demand. At the same time, elements found in seawater at low concentrations can contribute to ameliorating increasing demand for some elements, as can be seen from a 25% to 33% share of the Li extraction potential compared to Li demand scenarios (Greim et al., 2020). However, several materials are at such low concentrations that they cannot be considered a viable resource even compared to present demand levels.

Lithium extraction through chemical precipitation (Ahmad et al., 2019) and an electrochemical process using a system of λ-MnO_2/Ag electrodes (Joo et al., 2020; Kim et al., 2019) are the only two techniques that have been reported for lithium recovery from desalination brines. Other studies are either on salt solutions or salt lake brines (real (S. Kim et al., 2015; Missoni et al., 2016; Trócoli et al., 2015, 2017;), artificial (Trócoli et al., 2014), or simulated (Lawagon et al., 2018; Zhao et al., 2017, 2020a–c, 2021). Techno-economic analysis of the possibility of extracting Li from desalination brines using an electrochemical method with λ-MnO_2/Ag electrodes indicates that extraction is not economically feasible at present. The future production cost of extracting Li shows a strong dependence on the electrode lifetime and scrap value at the end of the electrode life. Improving the Ag electrode efficiency from the current 20% is another possible pathway to reducing the cost of Li extraction from desalination brines, and this aspect needs further investigation. The annual demand of silver for desalination brine treatment towards mid-century may be manageable, as stock accumulation over a 15-year period would lead to a demand of 13% of present annual production. However, studies show that silver production may peak before 2040 even based on historical regular demand (Sverdrup et al., 2014). More importantly, estimates show the need to (Louwen et al., 2016) and possibility of (Altermatt et al., 2018) substituting silver with copper in crystalline silicon photovoltaics and Ag recycling from decommissioned modules to avoid the possibility of supply shortage by 2030 (Heath et al., 2020) if copper-based solutions are not available (Li and Adachi, 2019). However, other types of electrodes may also overcome these challenges.

The electrochemical method has been developing fast in recent years, resulting in a number of new available cathode and anode materials for selective Li extraction. Latest studies on the electrochemical Li extraction (Zhao et al., 2020a–c, 2021) have shown promising results. However, the studies used a feed of simulated salt lake brines with a concentration of 0.16 g_{Li}/l, which is significantly higher than the 0.17 mg_{Li}/l content in seawater at 35,000 ppm. As an example, the Li extraction capacity of the system with graphene gauze modified Ni-rich cathode material and activated carbon anode material (rGO/NCM//AC) (Zhao et al., 2020a) is 13.84 $mg_{Li}/g_{electrode}$. Since one cycle takes 40 min, the extraction efficiency is 498 $mg_{Li}/g_{electrode}$/day with an energy consumption of 0.2 kWh/kg_{Li}. However, the feedwater of the system is up to 500 times more concentrated with Li than desalination brines, thus the observed efficiency cannot be directly applied to Li extraction from desalination brine discharge. Nevertheless, it represents a step towards a potential solution to the challenges facing the electrochemical technique. The Li purity after using the rGO/NCM//AC electrode is reported to be 93%, while the capacity retention is 80.8% for 30 cycles, which equals to a capacity loss rate of 23%/day. With further improvements, graphene electrodes may become a cost-effective replacement for the λ-MnO_2/Ag electrode system. However, the Ag electrode enables a higher purity of the produced Li, and higher efficiency, leading to a smaller mass requirement for the electrode.

Materials for ion-selective membranes are also actively developing nowadays, which can potentially allow direct lithium capture from brines (DuChanois et al., 2021) in the future. As well, the adsorption technology using the cooling crystallization method demonstrates a further efficiency improvement of the method, however, yet only for salt lake brines solutions (Wei et al., 2021). Besides that, a novel computational framework case study for selecting the best suitable process for possible lithium extraction from brines and seawater was presented by Mir Saber Salehi et al. (2021). With further technological development, highly selective Li extraction technologies can be extended to explore the possibility of Li recovery directly from seawater. The demonstration of such a concept has been reported by Liu et al. (2020). Another lab-scale concept by Li et al. (2021) describes direct battery-grade Li extraction from seawater using electrolyte membranes. Such a process shows a promising profitability due to electricity consumption of 76.34 kWh to enrich 1 kg of Li altogether with added value of co-products such

as hydrogen, chlorine and freshwater from the same process. Corresponding Li extraction systems might become an independent extraction facility for the almost endless Li resources worldwide, if a cost competitive system could be developed, which would overcome the long-term sustainability challenge of Li-based solutions for the energy transition (Greim et al., 2020).

One of the challenges of desalination brines treatment is the need for a multi-material extraction process to avoid salty brine discharge to the environment. Because NaCl alone constitutes 86% of all dissolved salts in seawater and, hence, in desalination brines as well (SeaAgri, 2015), its removal from the solution would increase the concentrations of other dissolved materials by 5% due to the volume reduction of the solution. Removing NaCl alongside the second most concentrated material, magnesium, would increase the concentration of the rest of the materials in brines by 6% compared to the initial brine materials concentrations. The concept of zero brine discharge has to overcome the high price of the process, which is mainly driven by electricity costs (Nayar et al., 2019). This requirement may partly be met by the projected cheaper renewable electricity cost in 2050 (Bogdanov et al., 2019; Vartiainen et al., 2020). Additional materials recovery from the separated salts would improve the economics of the process further, as co-benefits could be achieved. Davis (2006) has demonstrated a laboratory-scale project using electrodialysis to maximise freshwater recovery from seawater and reached a total material concentration from brines of 200,000 ppm.

Extracting Li alongside other materials is possible from geothermal brines (Bakane, 2013; Samco Technologies, 2018). A laboratory-scale project by Mroczek et al. (2015) showed that the lithium in geothermal brines can be extracted from the stream after recovering silica. A commercial geothermal plant combining electricity generation and Li extraction is planned to be commissioned in Germany in 2022 (Schaal, 2020). The plant will be able to produce 2000 t of lithium hydroxide annually from solutions of 200–400 g_{Li}/m^3 content. With other Li production facilities in Europe, it was estimated that there is potential for securing up to 80% of the European demand for Li by 2025 (Schaal, 2020). An even more ambitious project for Li extraction from geothermal brines using a high-capacity selective sorbent with an extraction efficiency of 90% has been reported for geothermal plants in California (Ventura et al., 2020). The typical Li concentration in geothermal brines of the area, is 211 ppm, compared to 0.34 ppm in average desalination brines. The cost of Li production is estimated to be around 4000 USD/t_{Li} for a commercial-scale geothermal plant with 20,000 t_{Li}/y production from a simulated brine solution containing about 400 ppm Li. The whole geothermal region in turn has resources of 600 kt of Li extraction annually. The majority of geothermal brines in the United States have a Li concentration of about 1–10 ppm, and only a few have more than 20 ppm of Li concentration (Neupane and Wendt, 2017), compared to the assumed 400 ppm for the cost estimation.

6. Conclusion

This study explores the material extraction potential of desalination brines corresponding to the volume of seawater desalination that is required to meet water stress driven demand projected for 2050. The key objective of the study was to investigate whether material extraction from desalination brines can supply a significant portion of projected material demand, particularly for critical materials, while also aiding in efforts to avoid discharge of concentrated brine into the environment. Analysis of the brine material content in 145 regions of the world based on three desalination scenarios showed that regions linked to both high water stress and high seawater salinity have not only high material extraction potential, but also that such regions as Pakistan alone can potentially supply up to 84% of the global Li demand in 2018 from desalination brines only. This is true also for other materials in brines and other regions with same initial parameters.

Investigation of Mg and Li, as examples of high and low concentration elements respectively, showed that the Mg extraction potential may exceed its future demand by significant amounts, whereas the Li extraction potential may only suffice to ameliorate supply pressure for this material. Nevertheless, Li extraction potential is still in the region of 33% of total Li demand in 2050. The difference in the supply potential of the two materials is due to the relative concentration difference of a factor of about 7600 for the elements. In both cases, however, the extraction potential is significantly higher than the present global demand. Thus, the Li extraction potential may be significant enough to ease the Li supply shortfall projected for the latter parts of the century. Several materials at low concentrations have too poor potential compared to present demand for extraction from desalination brines to be considered a viable resource. The results also show that regions with enormous desalination demand, such as Pakistan, could become key players in materials supply, for example for Li, and thus balance out global materials supply and reduce the supply burden on major exporters such as China.

If efficient and economic techniques for extracting critical elements can be achieved, water stress may be converted into an economic opportunity. High-concentrated elements can already be extracted directly from seawater in a cost-effective way, extraction of less concentrated elements however requires development of effective extraction techniques to overcome the drawbacks of low concentration and associated higher costs. Two techniques investigated in more detail in this work revealed significant techno-economic challenges. The relative concentration of Mg and Li jeopardises the possibility of extracting Li as a co-product of Mg to reduce total extraction costs. The possibility of using electrochemical separation using λ-MnO_2/Ag electrodes faces challenges due to the quantity and cost of the required silver. The attractiveness of this approach depends on future electrode efficiency, the lifetime and stability of the electrode, the cost of lithium, and options to substitute the electrode material. Overcoming such challenges would be a major milestone towards developing processes that allow the simultaneous extraction of multiple materials.

CRediT authorship contribution statement

Vitalii Lundaev: Conceptualization, Methodology, Software, Investigation, Data curation, Writing – original draft. **A.A. Solomon:** Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing, Funding acquisition. **Upeksha Caldera:** Investigation, Software, Writing – review & editing. **Christian Breyer:** Conceptualization, Methodology, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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